The compositional dependence of phase separation in InGaN layers

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•The aim of this work is to understand the occurrence of phase separation in InGaN layers of different compositions.

• InGaN layers of increasing InN content were grown by MOCVD. At InN contents of 3%, TEM images show a homogenous microstructure and selected area diffraction (SAD) patterns exhibit no satellite spots. InN contents of 12% result in a speckled contrast as shown in Fig. 1(a). Satellites, close to the fundamental spots are present in SAD patterns as shown in Fig. 2. They result from composition modulations lying in the (0001) growth plane. No satellites are observed along the [0001] direction, implying that phase separation is two-dimensional in nature. Samples containing InN fractions of between 22 and 28% have microstructures exhibiting much stronger contrast variations as shown in Fig. 1(b). Satellite spots in SAD patterns are further spaced from the fundamental reflections, implying shorter modulation wavelength. This trend continues on increasing InN content to 34%. Modulation wavelengths calculated from SAD patterns are given in Fig. 3.

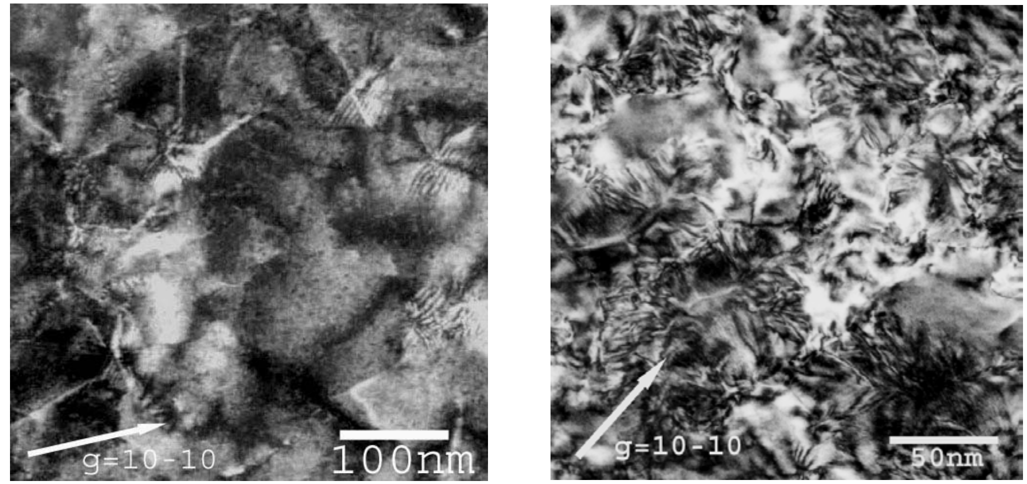

FIG. 1. (a) Dark-field plan view TEM images of $In_{0.12}Ga_{0.88}N$ showing speckle contrast and (b) $In_{0.22}Ga_{0.78}N$ showing domains with alternating light/dark contrast bands lying similarly oriented within a domain.

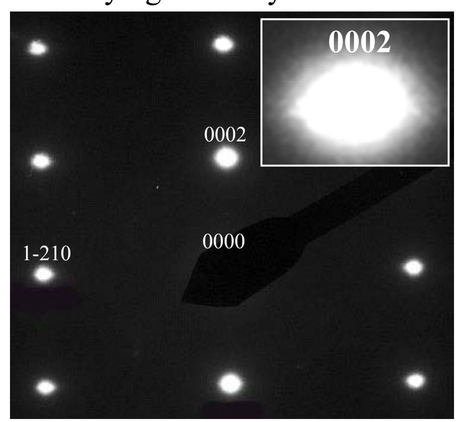

Fig. 2. (10-10) SAD pattern from $In_{0.22}Ga_{0.78}N$ and enlarged (0002) spot. Satellites lie within the growth plane.

InN fraction	Modulation wavelength (nm)	
	<11-20>	<10-10>
0.03	∞	∞
0.12	18+/-2	20+/-2
0.22	9+/-1	8+/-1
0.28	9+/-1	8+/-1
0.34	3+/-1	5+/-1

Fig. 3. Table of composition modulation wavelengths calculated for InGaN samples with increasing In contents.

Aim of the project:

A consensus has emerged that atomic species in mixed III-V layers, differing in their covalent tetrahedral radii, are not distributed at random on their respective sub-lattices. Two types of deviation from randomness have been observed in InGaN: phase separation and atomic ordering. The objective of this work is to understand how phase separation and ordering occur and how resulting microstructures evolve in these materials.

Research results:

The microstructures of the InGaN layers, as revealed by TEM, change substantially as the InN content is increased. At very low InN contents (3%), images show a homogenous microstructure with little contrast present in the image. This is consistent with the selected area diffraction pattern (SADP) and implies that phase separation does not occur in this sample. With higher InN contents (12%), a speckled contrast is observed in the images and domain boundaries appear to be present in some areas of the sample, as shown in Fig. 1 (a). This fine scale speckled microstructure is characteristic of strain associated with phase separation. Samples with InN contents of 22% and above have microstructures exhibiting much stronger contrast variations, as shown in Fig. 1 (b). This occurs because in addition to having shorter modulation wavelength, the amplitude of the composition modulations likely increases with InN content.

Fig. 2 shows a (10-10) cross-sectional SADP, taken from a $In_{0.22}Ga_{0.78}N$ layer. The enlargement of the (0002) spot shows that satellites are oriented along the [1-210] direction. The absence of satellites in the [0002] direction implies that phase separation is 2-D in nature and occurs on the surface of the growing layer.

A (0001) (SADP) obtained from a $In_{0.03}Ga_{0.97}N$ exhibits circular diffraction spots, implying that the layer is homogenous. On increasing the InN content to $In_{0.12}Ga_{0.88}N$, the diffraction spots become non-circular due to the presence of satellite spots around fundamental reflections. The presence of these spots is consistent with the occurrence of phase separation, in the form of composition modulations, along different crystallographic directions lying in the (0001) growth plane. The spacing of the satellite spots relative to the fundamental reflections is inversely proportional to the modulation wavelength and calculated modulation wavelengths are summarized in Fig. 3. The driving force for phase separation increases with InN content and kinetic constraints increase with decreasing growth temperature. Therefore, the wavelength of composition modulations should decrease with increasing InN content and our results are consistent with this.

Significance of this work:

The electrical and optical properties of mixed III-N semiconductors are strongly influenced by compositional uniformity and deviations from this. Phase separation in InGaN creates regions of potential minima (high In content) in which carriers recombine, therefore enhancing the luminescence behavior. However increased carrier scattering is predicted to result in decreased mobility in phase separated films. In this work we have gained a greater understanding of the mechanisms of phase separation and associated microstructures in InGaN.

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Education: Results of our studies have been incorporated into courses that we teach on “Growth and Processing of Semiconductors”. Specifically,
we bring out the role of microstructures in determining performance and reliability of light emitters and transistors.

Outreach: We strongly believe in the concept of REUs. We have three undergraduates working in our laboratories. Their research focus is on growth and characterization of group III nitrides semiconductors. This unique experience will prepare them well for academia or industry